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CASTINGS, STEEL

HOMOGENIZATION OF STEEL CASTINGS

OBJECT

To summarize and correlate the existing data and information available in the technical literature and in Watertown Arsenal reports concerning the effects of homogenizing heat-treatments upon steel castings which are to be used in the quenched-and-tempered condition.

SUMMARY OF RESULTS

1. A survey of the technical literature and Watertown Arsenal reports indicates:

A. The effect, if any, of preliminary homogenizing treatment upon the tensile properties of quenched-and-tempered cast steel is small. The increase in yield strength (for equivalent reduction of area) which can be produced by homogenizing treatment is definitely less than ten per cent. If there is any influence upon Charpy tensile "impact" energy, it is less than the random scatter of Charpy values found in testing steel castings which have been quenched and tempered.

B. The available data on the effect of homogenizing treatment upon macrostructure, before and after quenching and tempering, and upon microstructure after quenching and tempering, are indecisive.

C. No effect of homogenizing treatment upon ballistic properties of cast armor or upon hardenability of cast steel has been found. The information available on these points is meager, however.

D. The data are insufficient to permit inferences to be drawn concerning the influence of homogenizing treatments upon lustrous cavities, ballistic properties of armor-piercing projectiles, local hardness, erosion, corrosion, weldability, or x-ray diffraction pattern of quenched and tempered steel castings.

2. Calculations based upon known diffusion rates show:

A. Practical homogenizing heat-treatments can have no significant effect upon large-scale chemical segregation, such as that found between the center and the outside of an ingot or of a centrifugal casting. This is confirmed by reports of chemical analyses taken across sections of castings.

B. Interdendritic segregation of carbon will be largely eliminated by either the usual heating for quenching or a homogenizing treatment.

C. Interdendritic segregation of sulfur will probably not be affected by homogenizing treatments.

D. Available data on diffusion rates are not sufficient to determine whether or not interdendritic segregation of manganese, silicon, phosphorus, and alloying elements will be appreciably reduced either by heating for quenching or by homogenizing treatments.

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INTRODUCTION

There is considerable interest at Watertown Arsenal in the effect of homogenizing heat-treatments upon the properties of cast steel which is subsequently quenched and tempered. This arises primarily from uncertainty as to the need for the preliminary homogenizing treatment which has been customary for centrifugally cast guns (see Appendix A). The effect of such treatments on the ballistic properties of cast armor is also currently under discussion.

A homogenizing heat-treatment may be defined as a preliminary heat-treatment whose purpose is to increase the uniformity of the material. While any temperature above the critical range may be used for steel, the term is ordinarily restricted to treatments at 1700°F or higher. In industrial heat-treating 1850°F is generally the maximum practical temperature, but at Watertown Arsenal treatments up to 2200°F have been used. (See Appendix A.)

This report endeavors to review work which has been reported in the literature on the effects of homogenizing heat-treatments upon the physical properties (static tensile and Charpy), macrostructure (as shown by hot acid etch), microstructure, segregation, "lustrous cavities," ballistic properties, hardenability, hardness in local regions, resistance to erosion and corrosion, weldability, and x-ray diffraction pattern of cast steel after quenching and tempering. Although all of these characteristics may be of scientific interest, it should be remembered that only physical properties and resistance to erosion have been correlated with service requirements for guns, while only ballistic properties, and in certain cases weldability, have been correlated with service requirements for armor.

In the following sections all temperatures given in degrees Centigrade by the authors cited have been converted to Fahrenheit, to facilitate comparisons, and rounded off to the nearest 10°.

DATA AND DISCUSSION

Physical Properties

Although there have been numerous reports and published discussions about homogenizing heat-treatments of cast steel, many of them [1,2,3,4,5] present no experimental data concerning the physical properties (which may be considered of prime importance), while others give no experimental data of any sort.[6] In some cases the physical properties were determined on steel which was not treated subsequent to homogenization, so that the results obtained are not applicable to gun or other castings which are quenched and tempered.

Studies of Production Castings

The first comprehensive survey of the physical properties of centrifugal castings was made by Conner and Calvert[11] who reviewed approximately 200 production castings of varying composition, heat-treatment, size, melting and pouring practice. (Jenks' data[10] were included in this survey.) These authors concluded that slightly better static tensile properties (after quenching and tempering) result from the use of a 2100°F normalize for 25 to 28 hours than are obtained by homogenizing at lower temperatures or for shorter times, in the case of molybdenum-vanadium (0.10%) steels of between 0.35% and 0.45% carbon. The time and temperature of the normalizing treatment appear to be correlated closely with the date of casting and with melting and pouring practice. In view of the uncertainty in the conditions surrounding the processing of the castings, and the considerable scatter of the physical properties, it may be questioned whether the differences noted by Conner and Calvert are significant. They found no apparent difference in Charpy tensile "impact" values. Carter[7,8,9] reported neither any difference in Charpy tensile values nor in static physical properties between similar castings homogenized for different times at 2100°F.

Experimental Studies on Single Castings

Other workers, in an effort to reduce the number of variables, studied the effect of changing the homogenization treatment upon sections cut from a single casting. (This does not assure uniform initial material, since it is well known that the composition of regions within an ingot may differ widely and for centrifugal castings Gray[12] has shown marked longitudinal as well as transverse variations.)

One of the first investigators to report beneficial effects from preliminary high temperature treatments was Giolitti, who in his book[13] presents only two sets of data in which the final quenching and tempering are comparable. The experiments were performed on sections cut from an ingot containing 0.40% C and 2.02% Ni homogenized at various temperatures, slowly cooled to 1470°F, quenched in water and drawn at 1070°F for 2 hours. The results follow:[14]

Treatment	T.S. (lbs/sq.in)	% R. A.	Fremont "Impact"
2000°F, 11 hours	95,000	48	32
1830°F, 9 hours and 1920°F, 9 hours	104,000	49	32
2170°F, 10 hours 2120°F, 11 hours and 2000°F, 10 hours	95,000	49	32

The final treatments employed by Giolitti were not the same for the steel was not cooled through the critical range before heating for quenching; therefore, the results are not strictly comparable. The final heat-treatments for a second series of specimens from a plain carbon (.09% C) ingot were, however, identical. One sample was homogenized for 14 hours at 2100°F and the other received nothing but the final quench and draw, with the following results:[15]

	T.S.(lbs/sq.in)	Y.S.(lbs/sq.in)	% Elong.	% R.A.
Not homogenized	50,000	30,000	32	56
Homogenized	54,000	34,000	33	60

Since all other results presented in Giolitti's book were obtained from single test bars, and no experimental details are given in this case, it must be assumed that these are single test results. The significance of this data is therefore questionable.

The effect of homogenizing time and temperature for specimens taken from several centrifugal castings is presented in Table I. Each group of results represents specimens taken from a single casting. No significant trend can be noted except possibly in the effect of increasing the temperature from 1740° to 1830°F, but the number of tensile bars used in this test was not stated. This is the only large effect of homogenization reported in any temperature range.

Bender[19,63] and Waite,[20] studying chromium-molybdenum-vanadium centrifugal castings, noted no influence on the static or "impact" properties in various homogenizing times and temperatures of sections taken from single castings. The final treatment of the sections from each casting was identical. The results of these studies are presented in Table II.

TABLE I

Early Data on Homogenization of Molybdenum-Vanadium Centrifugal Castings

Temperature	Time	Y.S. (lbs/sq.in)	% R. A.	Tensile Charpy "Impact" (ft.lbs.)
		Haskell[16]		
1740°F	5 hrs.	66,000	27	
1850°F	8 hrs.	75,000	42	
2100°F	8 hrs.	76,000	48	
		+Haskell[17]		
2100°F	28 hrs.	82,000	61	36
2200°F	8 hrs.	81,000	59	38
2200°F	12 hrs.	80,000	61	40
2280°F	8 hrs.	78,000	62	36
		+Baker[18]		
2100°F	28 hrs.	74,000	51	24*
2200°F	4 hrs.	74,000	49	24*
2200°F	8 hrs.	75,000	53	27
2200°F	12 hrs.	73,500	43	27*
2200°F	16 hrs.	75,000	44	24*
2240°F	4 hrs.	72,000	53	25*
2240°F	8 hrs.	73,000	53	27*
2240°F	12 hrs.	74,000	56	26
2280°F	4 hrs.	75,000	53	29*
2280°F	8 hrs.	75,000	50	31*

+Averaged from 2 test bars
*Lustrous Cavities

TABLE II

Recent Data on Homogenization of Chromium-Molybdenum-Vanadium Centrifugal Castings

Casting No.	Temperature	Time	Y.S. (lbs/sq.in.)	% R.A	Tensile Charpy "Impact" (ft.lbs)
		White[20]+			
1	None	None	82,000	63	
1	1600°F	16 hours	79,000	62	
1	2000	2	76,000	65	
2	1600	6	84,000	62	
2	2300	2	86,000	65	
3	2000	6	76,000	67	
3	2000	16	74,000	67	
3	2300	6	76,000	65	
3	2300	16	[illegible]5,000	52	
		Bender[19]			
1	2200	16	101,000	62	44
1	None	None	97,000	64	34
2	2200	16	102,000	57	43
2	None	None	100,000	56	39
3	2200	16	95,000	58	30
3	None	None	93,000	51	53
		Bender and Furnas[43]+			
1	2200	16	95,000	58	30
1	None	None	98,500	51	38
2	2200	16	1[illegible],000	57	43
2	None	None	100,000	56	39
3	2200	16	101,000	62	44
3	None	None	97,000	64	35

+Average from two test bars

Experimental Treatments of Similar Castings

A few studies have been made using separate but supposedly identical experimental castings which were homogenized and given similar subsequent treatments, the tensile test bars being taken from corresponding positions in the castings. Using this method, McCoy[21] found an elastic limit of 75,000 lbs./sq.in. with 46% reduction of area on a single cast test block of plain carbon (.30%) steel which was homogenized for 28 hours at 2100°F, then normalized, annealed, quenched, and drawn, while 70,000 elastic limit and 40% reduction of area were obtained on a similar block which was simply quenched and drawn. Reed, Bolotsky, and Hurlich[22] cast nine eight-inch cubes from each of three .30% carbon heats, two heats being of high chromium-molybdenum steel and one of a nickel-chromium-molybdenum composition. The cubes were given homogenizing treatments of 8 to 36 hours at 1800, 2000, and 2100°F. After quenching and tempering, no difference in tensile properties was found among cubes of the same heat.

Comparisons of centrifugal castings normalized at 2200°F for 16 hours with similar castings not normalized have been made by Bender[19] and Birch[25] and are summarized in Table III. The improvement in tensile and Charpy values produced by normalizing is seen to be small, if it occurs at all. Bender and Pappas[64] later studied the effect of normalizing at lower temperatures for shorter times, with similar results.

Hurlich, Riffin, and Bolotsky[23] tested two cast plates from each of three heats of 0.30% carbon, 0.50% molybdenum steels, with

TABLE III

Studies of Effect of Homogenization
Of Similar Centrifugal Castings of
Chromium-Molybdenum-Vanadium Steels

Temperature	Time	Y. S. Lbs./sq.in.	% R. A.	Tensile Charpy "Impact"(ft-lbs)
		Bender[19]		
2200°F	- 16 hrs.	112,000	56	39
2200°F	- 16 hrs.	110,000	53	37
None	None	105,000	58	41
None	None	101,000	52	46
		Birch[25]		
2200°F	- 16 hrs.	63,000	70	46
2200°F	- 16 hrs.	72,000	62*	-
None	None	63,000	60*	46
None	None	67,000	65*	-

*Lustrous Cavities

TABLE IV

Study of Homogenization of Cast Plates of 0.30% C Medium Alloy Steels[23]

Heat	Temperature	T.S. Lbs./sq.in.	Y.S. Lbs/sq.in.	Elong. %	R.A. %	Charpy ft-lbs.
1	1900°F	110,000	89,000	22	56	--
1	1700°F	110,000	88,000	20	52	--
2	1900°F	125,000	108,000	20	56	29
2	1650°F	122,000	105,000	19	55	30
3	1900°F	118,000	97,000	22	58	34
3	1650°F	117,000	97,000	23	58	34

and without nickel, chromium, and copper. One plate was normalized for 8 hours at 1900°F and the other for 4 hours at 1650°F or 1700°F. The physical properties obtained after the final heat treatment are shown in Table IV; no differences are evident.

Webbers,[24] working with two complex-alloy experimental castings of similar composition, reported considerably higher properties as a result of a 1950°F treatment than were produced by an homogenization at 1700°F for a shorter time. The castings were made, however, by different manufacturers and were not comparable in any respect (except for composition and final heat treatment). The results of Merten[26] who obtained data before and after homogenization can also be disregarded, for the final thermal treatments were different in the two cases.

Summary

All the relevant information, with the single exception of Haskell's first report,[16] indicates that large variations in homogenizing times and temperatures have little, if any, effect upon tensile properties.

On the basis of the evidence, the effect of the omission of all treatments preliminary to the final heating for quenching is small, certainly less than ten percent of the yield strength for equivalent reduction of area. It appears that to determine if the small differences which have been reported actually exist, it will be necessary to make tests upon a large number of specimens under very carefully controlled conditions, and to subject the data so obtained to thorough statistical analysis.

Macrostructure

Macrostructure after Quenching and Tempering

Many of the investigators studied specimens taken from a single casting. This method is probably better than any of the others used, but when comparing the macrostructure of such samples, the variation of composition within one casting reported by Gray[12] must be remembered. Giolitti[14] and Haskell[17] reported that sections of castings homogenized at about 2200°F for 10 and 12 hours appeared less dendritic than sections treated at slightly lower temperatures for the same times or at nearly the same temperature for a shorter time. Giolitti compared 2% nickel 0.40% carbon steel at 2170, 2000, and 1830°F while Haskell's studies were restricted to centrifugal castings held at 2200°F for 8 and 12 hours and 2280°F for 8 hours.

Baker[18] found little difference in Baumann prints and in appearance after deep acid etching among sections of a centrifugal casting held for various times at 2100, 2200, 2240, and 2280°F. The specimens held for the longer times at each of these temperatures appear more uniform than the others at a magnification of 8 diameters.

White,[20] who used sections cut from three similar centrifugal castings, reported increasing homogenizing treatments from 2 hours at 1600°F to 2 hours at 2000°F or 16 hours at 1800°F produced progressively more "breaking up" of the dendritic structure than appeared in a sample quenched and tempered without prior normalizing. Specimens held for longer times at 2100, 2200, and 2300°F showed still more "breaking up" but no trend could be seen among them.

Kilberg[27] homogenized a cast plate 5 hours at 1750°F and another 5 hours at 1825°F. His photographs show slightly more dendritic structure in the plate treated at the lower temperature but the etching conditions were not stated.

Reed,[28] who treated cubes cut from two plates of chrome-molybdenum-vanadium steel and Reed, Bolotsky, and Hurlich,[22] who used a separate cast block for each sample, found no difference in macrostructure as a result of various homogenizing treatments in the range 1800 to 2100°F.

Bender[19] and Bender and Pappas[63] compared sections of similar castings and of the same casting which had been homogenized for 15 hours at 2200°F with sections which had received no treatment prior to the quenching and tempering, and reported they were alike in macrostructure. From the pictures presented in one report,[63] however, there appears to be less segregation in a homogenized section of one casting than in a section which was simply quenched and tempered.

The data on the effect of homogenizing treatments upon macrostructure of steel castings subsequent to the quench-and-temper are contradictory. On the basis of the recent ingestigations[18,19,20,22,28,63] it is probably safe to conclude that increase of temperature or time above a few hours at 2000°F has very little effect despite the opposite results obtained in earlier work by Haskell and Giolitti. It is, however, impossible to decide from the existing data whether homogenizing at 2000°F results in a macrostructure different from that obtained by a lower or no homogenizing treatment.

The macrostructure of sections taken from the same or similar castings is difficult to interpret because of the variation of composition within and between the castings and the possible variation of casting conditions. Furthermore, slight variations in time and conditions of etching and, if a photograph is used, in contrast and exposure time, may produce wide variations in appearance. The broad interpretation of the data may be, that, considering the nature of the test, the effect of homogenizing treatments on macrostructure is indecisive, but there may be some progressive "breaking up" of the dendritic structure with increasing time and temperature.

<u>Macrostructure of Castings Not Quenched and Tempered</u>

Even though this report deals primarily with the results obtained from studies of castings following quenching and tempering in which the final thermal treatments of the specimens to be compared are identical, results obtained from studies of macrostructure immediately subsequent to homogenization are included for the sake of completeness.

Butler[2] homogenized discs, cut from a centrifugal casting, for various times up to 120 hours at 2100°F. He reported that increasing the homogenization time "improves the structure, making the zones less marked, breaking up the dendrites, and refining particles and streaks," and found the first appreciable improvement at 16 hours and "a very great improvement" at 60 hours. He also states that Baumann prints show similar trends but the photographs he includes do not substantiate this statement. Ash[4] used a series of experimental chromium-nickel-molybdenum steel centrifugal castings containing 0.15%, 0.30%, and 0.45% carbon, respectively. Ash macroetched the discs immediately following treatments of various times up to 110 hours at 1830, 2100, 2200, 2280°F and after a subsequent normalizing and annealing. He concluded that considerable homogenization was necessary to "remove macro-dendrites;" however, the extreme scatter of his results and his failure to include photographs in his report prohibit any re-evaluation or re-interpretation of his data. Haskell,[17] White,[20] and Reed, Bolotsky, and Hurlich[22] obtained results, on specimens which were merely homogenized, which duplicate their findings after quenching and tempering (see page 11.) The summary of the effect of homogenization on macrostructure given on pp. 12f. therefore, suffices for macrostructure immediately following the homogenizing treatment.

Microstructure

Some of the investigators[3,26] of the effect of homogenizing heat treatment upon the microstructure of cast steel have used specimens which received final heat-treatments so different that the structures cannot be considered comparable. Others[2, 4, 13, 20, 22] have studied microstructure after homogenization only; here, also, there is some doubt as to whether the structures reflect differences in homogeneity, because variations in austenitic grain size and in cooling rate may have resulted from the several homogenizing temperatures. Carter[9, 29, 30] and Ash[4] investigated the effect of homogenization on the microstructure of steel subsequently normalized and annealed.

This review of the effect of homogenization on the microstructure of cast steel must be limited to that obtained after quenching and tempering, since the present report deals with material used in this condition.

Giolitti[14] presents photomicrographs of specimens homogenized at 1830, 2000, and 2170°F and then quenched and tempered. The samples, which were etched in hot, dilute sulfuric acid, relief-polished, and re-etched with a solution of nitric acid in amyl alcohol, appear similar. Carter[1] found that treatments for 8 to 16 hours at 1830 and 1920°F did not affect equiaxed dendrites, as shown by nital and by copper chloride etch,[34] but did produce slight "differences" in columnar dendrites as compared with sections from the same casting treated at lower temperatures for shorter times. Examining similar production castings,[7,8,31,32] Carter noted less severe dendritic segregation, with nital etch, in a casting homogenized 28 hours at 2100°F than in one homogenized 22 hours.

It was further reported by Haskell[17] that the dendritic segregation brought out by nital etching decreased as the temperature increased. Haskell etched discs, homogenized at different temperatures, in copper chloride etching reagent, and the "dendritic segregation" appeared to be most in the specimen treated at the highest temperature. This phenomenon he calls "reversion to the cast state." Using copper chloride solution, Baker[18] confirmed the results of Carter in that increasing time appeared to decrease the segregation and found no reversion, nor could he specify any consistent variation in amount of segregation with homogenizing temperature. Using nital etch he not only could discover no trend but noted little difference between specimens variously treated.

Contrary to the previous investigators Reed,[28] in studying homogenization of cubes cut from a single ingot, reported that the degree of diffusion appeared to increase somewhat with increasing temperature when the specimens were given a single air quench and temper. Samples which were given a double air quench, however, reflected no difference correlated with the temperature of treatment. Furthermore, Reed, who employed both nital and copper chloride etching solutions, found no effect of time at temperature in any case. Bender obtained conflicting results in comparing castings normalized and not normalized; in one case[19] the treatment had no influence on microstructure, and in another[63] greater diffusion was reported in the normalized castings. However, several of the micro-photographs which were presented may be interpreted so as to contradict this latter conclusion. Other investigators[22] note no effect of homogenization temperature on specimens etched in nital while still another[20] reports no trend toward decreasing segregation as the time and temperature of treatment are increased, using ~~both~~ nital ~~and ferricyanide~~ reagent, and the results of a third survey[27] are indecisive.

Hurlich, Riffin, and Bolotsky[23] compared castings, from each of three heats, normalized for various times and temperatures; they etched the specimens in copper chloride, nital, ferricyanide, and nital plus picral. The results so contradict each other that it may be concluded that no definite differences resulted from the various treatments. Confirming this variation in appearance with different etching reagents, Reed and Hurlich[33] attempted to classify three rolled plates of similar composition on the basis of "segregation" as revealed by five etching reagents, and rated them in four different orders. Since there is doubt as to the significance of the structures brought out by the various etching reagents and discordance of the results, the correlation, if any, of the microscopic data with homogenization treatment is virtually impossible.

Segregation

Two types of chemical segregation may be of importance in steel castings.[35] The first is interdendritic segregation, which results in chemical inhomogeneities over distances of a fraction of an inch. The other may be called "large-scale segregation," and refers to differences in composition between volumes several inches apart, such as the top and the bottom of an ingot, or the center and the outside of a centrifugal casting. Both varieties of segregation arise because the last metal to solidify (interdendritic material, top of ingot, center of centrifugal casting) is richer in carbon and other elements than that which solidifies earlier (dendrites, bottom of ingot, outside of centrifugal casting), and there has been interest in elimination of both by homogenizing heat-treatments.[11] However, since the scale of the two is different, it may be expected that they will be differently affected by such treatments.

The effect of homogenizing heat-treatment upon segregation in steel castings may be calculated from measured diffusion rates, provided certain simplifying assumptions are made. Consider a case in which the concentration gradient occurs in one direction only, and initially (at time $t = 0$) decreases exponentially with x^2, where c = concentration increment (actual concentration minus a constant "background concentration") and x = distance along the gradient from the point of maximum concentration. It will also be assumed that $c \rightarrow 0$ as $x \rightarrow \pm\infty$ for all values of t. These should be reasonable first approximations for interdendritic segregation, where there is a narrow interdendritic region of high concentration and a wider volume within the dendrites of lower and relatively constant concentration. They should also fit large-scale segregation of the type found in centrifugal castings, where the concentration of several elements increases relatively rapidly near the inner surface.[2,5,12,16,17,36,37,38,39] In this case only half the distribution will be used since $x = 0$ at the inner surface, but this will not affect the result.

From Fick's Law[40] may be derived the general diffusion equation,

$$\frac{dc}{dt} = D \frac{d^2c}{dx^2} \qquad (1)$$

Assuming that D is independent of c, equation (1) may be solved using the boundary conditions mentioned in the preceding paragraph, giving:

$$c = \frac{c_0 x_0 \, e^{-\frac{x^2}{4Dt + x_0^2}}}{\sqrt{4Dt + x_0^2}} \qquad (2)$$

Here c_0 will equal the initial concentration increment at the maximum and x_0 will be the value of x at which

$$c = \frac{c_0}{e}, \qquad (3)$$

thus being a measure of the width of the segregate zone. From equation (1), it will be found that the time for the concentration increment c at $x = 0$ to fall to half its initial value will be

$$t_1 = \frac{3x_0^2}{4D}, \qquad (4)$$

This may be called the "half-homogenization time."

Reliable data for the rate of diffusion of carbon in austerite as a function of temperature have been published recently by Paschke and Hauttmann,[41] by Wells and Mehl,[42] by Ham, Parke, and Herzig;[43] their results are in substantial agreement. The values obtained by Wells and Mehl show that for a first approximation D may be considered independent of c; they also show that the effects of grain size, of the usual impurities, of oxygen content, of manganese up to 2½%, and of nickel up to 2% are negligible.

Ham, Parke, and Herzig demonstrated that the effect of molybdenum is slight. No data appear to be available as to the effects of chromium or of vanadium, but they are probably small. It, therefore, appears justifiable to use $D = 14.5 \times 10^{-7}\ cm^2/sec.$ at 2200°F, as given by Wells and Mehl's results for 0.30% carbon and $D = 1.2 \times 10^{-7}\ cm^2/sec.$ at 1650°F, obtained by a slight extrapolation from their figures.

Substituting these values in equation (4), and choosing various values for x_0, there is obtained for the half-homogenization time t_1 of carbon in austenite:

x_0(cm)	10^{-4}	10^{-2}	10^{-1}	10^{0}	10^{1}
t_1 at 1650°F	6×10^{-2} sec.	10 min.	15 hr.	67 days	19 yr.
t_1 at 2200°F	5×10^{-3} sec.	50 sec.	$1\frac{1}{2}$ hr.	6 days	2 yr.

Thus, noting that $2x_0$ may be considered the "width" of the high carbon zone and that 1650°F is the quenching temperature and 2200°F the homogenizing temperature which have been used for low carbon steel centrifugal castings (see Appendix A), it is evident that carbon inhomogeneities of the size of pearlite lamellae ($x_0=10^{-4}$ cm) will disappear in a fraction of a second at the quenching temperature. On the other hand, carbon differences between the inner and outer surfaces of a centrifugal casting ($x_0 = 10^{1}$ cm) will persist for years even at the homogenizing temperature of 2200°F. For interdendritic segregates, which have[20,27,63] a width of the order of 1/8" to 1" at a magnification of 100 diameters ($x_0=10^{-2}$ cm), the carbon content will be equalized within an hour at the quenching temperature.

The only available data on the diffusion rate of manganese in austenite appear to be the rough determination of

Paschke and Hauttmann (loc. cit.), who found it to be about 1/100 the (extrapolated) rate for carbon at 2640°F. There is, however, no way of extrapolating their manganese rate to lower temperatures without further data. The best that can be done is to assume that it remains of the order of 1/100 the carbon rate. This would mean that the half-homogenization time for interdendritic segregation of manganese ($x_0 = 10^{-2}$ cm) at 1650°F would be perhaps 10 to 20 hours and at 2200°F would be one or two hours. On this basis, the usual hold at the quenching temperature would reduce the manganese segregation somewhat and a homogenizing treatment of 16 hours at 2200°F would produce substantially complete removal of interdendritic manganese segregation.

Bramley, Haywood, Cooper, and Watts[44] (whose work has, however been criticized by Wells and Mehl[42]) have determined diffusion rates for phosphorus and sulfur in austenite. They reported the phosphorus rate to be of the order of 1/100 and the sulfur rate 1/1000 the carbon, which means that phosphorus segregation will be decreased at about the rate described above for manganese, while interdendritic segregation of sulfur will not be appreciably affected by homogenizing treatments. (Of course the solubility of sulfur in austenite is very small[45].)

There appears to be no information available on the diffusion rates of alloying elements or silicon in austenite; their order of magnitude will probably not differ greatly from that for manganese.

Thus it is clear that the large-scale segregation from center to outside of a centrifugal casting will not be reduced by homogenization. This is confirmed by segregation analysis studies by Butler,[2] by Haskell,[17] by Sloan,[5] and by Gray,[12] who found the only effect of homogenizing treatments to be decarburization at the inside and outside surfaces. Interdendritic segregation of sulfur will not be affected by homogenizing. It appears possible that homogenizing treatments will remove interdendritic segregation of manganese, phosphorus, silicon, and alloying elements, while the usual quenching temperatures and times will not. However, the data on these elements are so scanty that it is also possible that any or all will either be eliminated by quenching treatment or not be appreciably affected by homogenizing treatment.

<u>Lustrous Cavities</u>

"Lustrous cavities" are a phenomenon which has been frequently reported in centrifugal steel castings. They have been found on macro-etched surfaces,[18,46] under the microscope[16,17] and on fracture surfaces.[18,20,47,48] In tensile test bars they appear to be associated with lowered values for elongation and reduction of area.[20] The frequency of occurrence has been found to rise with the carbon content of the steel.[46,61]

Donald is apparently the only investigator to study the effect of homogenizing upon the occurrence of lustrous cavities. He reviewed approximately 50 production centrifugal castings, some of which were normalized $7\frac{1}{2}$ hours at 2100°F and others 4 hours at 1740°F, and at first stated[49,50] that the higher normalizing treatment produced fewer lustrous cavities. Later,[51] however, he concluded that the decrease in frequency was caused by a change in pouring practice (use of a smaller spout), which was made at the same time as the increase in normalizing temperature, and not by the latter. This is in accord with the explanation of the formation of lustrous cavities given by Reed[46] and by Portevin,[48] (i.e., the cavities are "micro-pipes" caused by interdendritic shrinkage of solidifying steel), and with Portevin's statement that they can be eliminated by proper foundry practice.

Ballistic Properties

Armor

It appears to be widely held that a homogenizing treatment is necessary to obtain satisfactory ballistic properties in cast armor plate, at least when highly alloyed steel is used. A literature search has, however, failed to reveal experimental work on this matter with two exceptions:

Kilberg[27] studied four cast plates, two 1.07" thick and two .83" thick, from a heat of 0.40% carbon, 1.15% chromium, 0.75% molybdenum, 0.11% vanadium steel. One of each thickness was normalized 5 hours at 1750°F, the other at 1825°F. No significant difference in resistance to penetration was found, as indicated by the following values obtained for the ballistic limit:

Thickness	Normalizing Temperature	Brinell Hardness	Ballistic Limit (ft/sec.)
1.07"	1825°F	420	2790
1.07	1750°	446	2760
.83	1825°	420	1920
.83	1750°	430	2100

The 1.07" plate homogenized at 1750°F failed in ballistic shock test, but Kilberg attributes this to its excessive hardness and not to the homogenizing treatment.

Hurlich, Riffin, and Bolotsky [23] took two plates from each of three heats of low carbon low alloy steel, one being of the manganese-molybdenum type, one molybdenum-nickel-chromium, and one molybdenum-nickel-chromium-copper. One plate from each heat was homogenized for 8 hours at 1900°F and the other 4 hours at 1650° or 1700°F. The two were then given the same final heat treatment and subjected to ballistic penetration, shock, and projectile-through-plate tests; they behaved similarly in all cases. The penetration values were:

Heat	Homogenizing Temperature	Thickness	Brinell Hardness	Ballistic Limit (ft/sec)
A	1900°F	2.05"	229	1740
A	1700°	2.00	223	1780
B	1900°	2.14	277	2020
B	1650°	2.11	269	1910
C	1900°	2.22	241	1940
C	1650°	2.23	245	1990

Projectiles

There seem to be no data available concerning the effect of homogenizing heat-treatment upon the ballistic properties of cast steel armor-piercing projectiles.

Hardenability

Studies of the effect of homogenizing heat-treatments upon the hardenability of cast steel have been reported by Webbers and by Hurlich, Riffin, and Bolotsky.[24] Webbers' work, however, cannot be considered significant because of his experimental errors, mentioned on page 10. The data of Hurlich, Riffin, and Bolotsky [23] show no appreciable difference in Jominy hardenability curves between cast plates homogenized 8 hours at 1900° and 4 hours at 1650°F or at 1700°F. They compared two plates from each of three heats of 0.30% C medium alloy steel.

Local Hardness

Butler[2] made a Vickers hardness survey of cast steel before and after homogenization in an attempt to find out whether such treatment improved the uniformity of the material. He reported that it did, but his data hardly substantiate this conclusion, and since the final conditions were not comparable, it does not appear that his results need be considered. White[20] used the Knoop hardness tester to survey material homogenized, quenched, and tempered and material quenched and tempered without homogenization. He found somewhat less spread of hardness in the sample which was not homogenized. However, since he used separate castings for the two conditions, this may not be significant.

Erosion

There has been some theorizing[11] as to the effect of homogenization upon the erosion characteristics of cast guns. This seems to have arisen because of a remark of Ritchie[52] who noted an investigation which had shown that increasing the amount of hot work given to forged guns decreased their erosion. He stated that this might be attributed to the breaking up of segregations and commented that it would be interesting to observe the resistance to erosion offered by centrifugally cast guns. However, it appears that no experimental work has been done on the effect of homogenization upon erosion resistance.

Corrosion

A literature search has failed to disclose any investigations of the influence of homogenizing treatments upon the corrosion of quenched-and-tempered cast steel.

Weldability

Hurlich, Riffin, and Bolotsky[23] made two-bead weldability tests on castings from three heats of 0.30% carbon heat-treated alloy steel, comparing samples homogenized 8 hours at 1900°F with others homogenized 4 hours at 1650° or 1700°F. The scatter of the values they obtained is, however, so great that it is not possible to draw any conclusions from them.

X-Ray Diffraction Data

No reports dealing with the effect of homogenizing treatments upon the x-ray diffraction pattern of quenched-and-tempered steel castings have been found.

A P P E N D I C E S

APPENDIX A

HISTORY OF THE HEAT TREATMENT AND COMPOSITION OF CENTRIFUGAL GUN CASTINGS AT WATERTOWN ARSENAL

The first few centrifugal castings made at Watertown Arsenal, in 1925, were of a plain carbon steel. Alloy additions of manganese, molybdenum, chromium, and of nickel were soon tried, however. The heat treatment generally consisted of a normalize at 1560° - 1740° F, an anneal at about 1550° F followed by rough-machining, a water quench from 1560° - 1650° F, and a temper at 1070° - 1250° F. The time at each temperature was 2 to 6 hours; the castings ranged from 75 mm gun to 155 mm howitzer. Transverse physical properties obtained were approximately 65000 lbs/sq. in. yield strength (0.01% set) and 45% reduction of area.[37]

The earliest attempt at a homogenizing treatment was made on casting No. 33, which was normalized for 4 hours at the higher temperature of 1830° F in an unsuccessful attempt to "break up" the dendritic structure shown by macro-etching.[37]

The composition first standardized seems to have been 0.30 - 0.40%C, 0.50-0.80% Mn, 0.20-0.40% Si, 0.25-0.35% Mo, heat-treated with the 1740° F normalize, anneal, quench, and temper mentioned above, and used primarily for 37 mm and 75 mm infantry mortars.[11, 53]

Presumably as a result of Lester's[54] finding that 0.10% vanadium refined the grain of the steel as cast, this element was added in 1930. Thus, for castings Nos. 150-300 (a variety of guns including many 75 mm howitzers and 3" A.A. liners), made in 1930-32, the composition C 0.40%, Mn 0.70%, Si 0.25%, Mo 0.30%, V 0.10% was generally used, with a heat-treatment consisting of 1740° F normalize, 1560° F anneal, 1580° F water quench, and 1290° F temper with furnace cool. This gave a yield strength of 65-75000 psi with 45-55% reduction of area.[38, 53]

In 1932 a period of experimentation in heat-treatment began. Apparently as a result of Giolitti's recommendations[13] (made in 1921), high-temperature long-time homogenizing treatments were tried,[11] together with a variety of complex procedures possibly suggested by the practice for gun forgings in the preceding war. For example, the following treatment was considered for 3" A.A. liners;[11]

2100° F 28 hours air-cool
1740° F 9 hours air-cool
1560° F 9 hours air-cool
1200° F 5 hours furnace-cool
Rough-Machine
1580° F 9 hours water-cool
1270° F 8 hours furnace-cool
1610° F 9 hours water-cool
1270° F 6½ hours furnace-cool

Here the 2100° F homogenization was supposed to remove dendritic segregation, absence of which was stated to be desireable in order to reduce erosion and obtain optimum physical properties. The subsequent normalizing treatments at 1740° and 1560° F were intended to refine the grain. (It was thought that several cycles of slow heating and rapid cooling through the critical range were required for grain refinement.) The 1200° F temper was presumably given in order to increase machineability and to remove stresses which might cause distortion during machining. (This temper and the preceding 1560° normalize were often replaced by an anneal.) The double quench-and-temper was suggested because it had been found to give higher strength than the first quench-and-temper alone (which, it should be noted, involved a lower quenching temperature and longer temper than did the second quench-and-temper). In addition, there was to be the original cooling in ashes of the casting when first removed from the mold, and final "cold-working" (autofrettage) of the heat-treated gun, followed by a "soak" at 570° F to straighten the stress-strain curve produced by "cold-working". The ash-cooling has been standard since chill molds were adopted after the first few castings [55, 56] and the "soak" has always been used on "cold-worked" guns. [55, 57]

In this period Carter [9, 29, 30] found that two production castings homogenized 28 hours at 2100° F displayed less dendritic structure under the microscope, after normalizing and annealing, than did one held 22 hours at the same temperature. (Other reports by Carter [7, 8] show less dendritic structure with 22 hours than 28, but since these papers dealt with other subjects no note was taken of this fact.) Haskell [16] concluded from his experimental work that a homogenizing treatment of 8 hours at 1850° F produced higher tensile properties than 5 hours at 1740° F. (This is the only paper in which a definite effect upon physical properties after quenching and tempering has been found; see page 10.) From other data which were much less decisive Haskell concluded that vanadium additions strengthened the castings. Butler [2] inferred on the basis of a macro and microstructure study of an as-homogenized casting that "28 hours is apparently the minimum time at (2100° F), to be employed", while Conner and Calvert [11] reviewed production guns (see comments on page 3) and recommended the use of 0.10% V and the following heat-treatment for all castings:

2100° F	25 hours	air-cool
1740° F	9 hours	air-cool
1560° F	9 hours	furnace-cool
1610°-1650° F		water-quench
1260° F		furnace-cool

This differed slightly from the treatment which had become standard in 1933 in that the latter employed an air cool from the 1560° treatment, followed by a 5 hour temper at 1200° F. After the publication of Conner and Calvert's paper in 1934, however, their recommendations were adopted, with the homogenizing time increased to 28 hours and the tempering temperature to 1270° F. This procedure was used until 1938 for 3" A.A. liners and tubes and 75 mm pack howitzers which were required to have 65,000 lbs/sq.in. yield strength and 30% reduction of area, minimum, before cold-working. [17, 18, 53, 56]

For several months in 1934-36, however, production was confined to 1.1" machine guns, for which 95,000 lbs/sq.in. yield strength and 30% reduction of area were specified. To provide the increased strength in these guns, the molybdenum-vanadium composition was modified temporarily by raising the manganese to 0.95 - 1.05%, while the tempering temperature was lowered to 1200° F. Apparently on account of the small section of these guns, the homogenizing time was reduced to 8 hours (at first at 1920°, later at 2100°, finally at 2200° F) and the normalizing and annealing times decreased to 5 hours. [53]

In 1934 Donald [59] carried out experimental work on and recommended the adoption of a steel containing 2.25% Mn and 0.30% Mo, with carbon below 0.30% to reduce lustrous cavities (see page 22). This was not done, but the carbon of the standard Mo-V composition was lowered to 0.25 - 0.30% for 75 mm and 3" weapons and the manganese raised, for a short while, to 0.80 - 1.10%. [53]

Haskell [17] and Baker [18] reported in 1937 that there is little difference in microstructure, macrostructure, or physical properties, after quenching and tempering, between castings homogenized 16 hours at 2200° F and those made with the older practice of 28 hours at 2100° F. The 2200° F hour treatment was, therefore, adopted in order to reduce the furnace time required. In 1938 Reed and Carter [60] experimented both with sections from one centrifugal casting and with a number of production castings in an effort to find out whether the 1740° F normalize and the 1530° F anneal could be omitted. They reported that these treatments had no effect upon physical properties, microstructure or macrostructure of the guns and recommended that the 1740° F normalize be omitted; this was done shortly thereafter. Reed and Carter found that the anneal could not be omitted when machining preceded the quenching and tempering because castings straightened (preparatory to machining) immediately following the homogenizing treatment tended to break at small surface defects. They suggested machining after the quench-and-draw. This was tried and found successful. The annealing treatment was, therefore, omitted and the production heat-treatment reduced to homogenization, quench, and temper. This has remained constant since 1943 and consists of the following for guns to be cold worked (3" liner and tubes, 105 mm howitzer, and 90 mm guns), which must have a minimum yield strength of 65,000 lbs/sq.in.:

2200° F	16 hours air-cool
1550°-1580° F	5-7 hours water-quench
1290°-1330° F	6-7 hours furnace-cool

The treatment for 1.1", 37 mm, and 40 mm guns (for which 95,000 lbs/sq.in. minimum yield strength was specified) differ from this only in using a tempering temperature of 1180-1200° F for the breech and 15° F higher at the muzzle.[53]

In 1937-8 another study by Reed [43] confirmed the earlier finding of Conner [61] that lowering the carbon from 0.30% to below 0.20% considerably reduced the number of lustrous cavities (see page 22). 0.15-0.20% carbon was, therefore, adopted together with an addition of 0.90-1.10% chromium in order to balance the loss of strength which would otherwise occur. [30] Thus, from 1938 to 1942 the composition used was: [53, 56]

Mn	Si	P	S	Cr	Mo	V
.60-.90%	.15-.25%	.02% max.	.02% max.	.90-1.10%	.45-.55%	.10%

The carbon content was raised in 1939 to 0.18-0.22% for the 65,000 yield strength guns and to 0.20-0.25% for the weapons required to have 85,000 lbs/sq.in. minimum yield strength.

To conserve chromium and vanadium, the composition was changed in October 1942 to:

C	Mn	Si	Cr	Mo	V
.24-.28%	.80%	.35-.55%	.50%-.70%	.45-.55%	.08%

For the smaller guns (37 mm and 40 mm) 0.50% chromium was aimed at, and in the larger guns (105 howitzer and 90 mm gun) 0.70% chromium was desired. The carbon content was raised to 0.30-0.35% on a group of 37 mm guns for which a mimimum yield strength of 120,000 lbs/sq.in. was prescribed. [62]

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